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# GPR imaging of recent coastal-dune development: effects of sand nourishments

**A contribution to the projects 'Kustlijnzorg'and 'Kustveilig'**

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foredune, beach, artificial sand nourishment, dune growth, geological processes, coastal management, ground-penetrating radar, storm surge



## Summary
Much of the Dutch coast has been subject to structural erosion. From 1990 the policy of dynamic preservation has been implemented, involving sand nourishments at selected locations along the coast. The developments of the coast are monitored annually by coastal-profiling transects. Analyses of monitoring data combined with visual inspection has shown that the structural erosion has decreased or even turned into coastal progradation after 1990, following implementation of the new policy. However, the monitoring data supply only limited information on system-related geological processes behind the observed changes, mostly because of its relatively low measurement frequency and lack of integration with other data types.
The aim of this study is to establish the origin of sedimentary elements within the beach-foredune area and to determine their decadal-scale preservation potential under the present nourishment policy. An additional aim is to demonstrate temporal and spatial accretion/erosion variability along nourished coasts. Both goals are achieved by an integral approach using ground-penetrating radar (GPR) and coastal-monitoring data of two sites along the western Netherlands coast, and combining these data with meteorological and other process information. This procedure can be applied at any desired location along the coast.

At Heemskerk aan Zee, sand nourishments have never been applied. Here the foredune foot has eroded 1.0 m/yr in the period 1965-2008. GPR imaging reveals historical storm-surge deposits within the foredune, as well as sequences of aeolian sediment accretion at the landward side of the frontal dune. At Bergen aan Zee, coastal erosion has been stopped by frequent sand nourishments. As a consequence, the dune foot has migrated seaward by 30-50 m during the period 1990-2008. GPR shows a number of sedimentary facies within the prograding foredune, including nourishment embankments, several wind-blown units derived from nourished sand, and prograding beach deposits. Integration of annual monitoring data and GPR shows that 21 % of the accreted volume originates from water-lain embankments constructed in 1990/91, 11 % from 1993 upper beach sands, 36 % from year 2000 nourishments (partly water-lain, mostly wind-blown), and the remaining 32 % from the period 2001-2008 (entirely in the form of wind-blown nourishment sands). The net volume of accumulation ranges from 180 to 233 m3/m over a lateral distance of 530 m.
Almost all sand of the nourishments applied prior to 2000 has been washed away. Analysis of meteorological data suggests that 1999 storm surges are responsible for this erosion. After 2000, structural accumulation has taken place along the dune foot in the form of nourishment sand redistributed by wind. This relative longevity can be attributed to a combination of shoreface nourishments (source) and favourable meteorological conditions.
Field observations during a storm surge in 2007 have demonstrated that water-lain embankments are more resistant against wave erosion than nourished sand redistributed by wind. This makes the composition of the nourished sediment, and the way it is deposited on the upper beach, an essential element in the endurance of nourishments.

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# 1 Introduction

The Dutch coast has been subject to persistent erosion and landward retreat throughout at least the last centuries, but presumably for up to 1,500 years. The long-term erosional trend and the damage caused by a series of storm surges in 1990 prompted the definition of the “Reference Coast Line” (RCL), which corresponds roughly with the position of the coastline at that moment. The RCL concept defines a minimum volume of the beach-foredune area that is to be maintained. Maintenance takes place in the form of sand nourishments. Locations and volumes of these nourishments are determined on the basis of year-to-year trends as derived from coastal monitoring. Precondition is that, in controlling structural erosion, the natural behaviour of the sandy coastline is maintained as much as possible. The so-called “dynamic preservation” of the coastline is achieved by the application of shoreface- and beach nourishments (Rijkswaterstaat, 1990). At places where safety is not at risk, nourishments are rarely or not applied, and limited breaching, scarp formation and blowout of foredunes is allowed or even stimulated. Here, increasingly liberal dune-maintenance policies are being implemented.
On an annual basis, about 12 Mm3 sand has been nourished at selected places along the Dutch coastline since the year 2000. Prior to 2000 this volume was about 6 Mm3. This volume was used for raising and widening the beach itself and for constructing sand embankments* against the foredunes (see vocabulary for explanation of marked* terms). Following later insights (Nourtec, 1997) sand has since also been placed on the shoreface around the 5-6 m depth mark (near the outer beaker bar), allowing currents, waves and wind to redistribute the sand to adjacent areas.

Since 1965, the development of the coastal zone has been monitored by means of coastal profiling (called Jarkus). Decadal shoreface, beach and foredune development can be analyzed using this morphometric database. The Jarkus database contains elevations for cross sections spaced apart 250 m (corresponding with the beach pole grid). These elevations are measured annually along the entire Dutch coast (cf. Arens & Wiersma, 1984). The profiles stretch from about 1000 m seaward of the low-tide line up to at least the dune foot. The supratidal part of the profiles has been measured by airborne laser altimetry (LIDAR) since 1996. Earlier profiling of the land part was achieved by topographic levellers and aerial photography. Annual measurements extend landward to at least the first top of the (fore)dune. Year-to-year variability in measuring and processing techniques can hamper straightforward analyses of the net changes of profiles (Arens, 2009). Additionally, the Jarkus database solely represents annual registrations of in the topography of the beach-dune profile. Hence, little can be said on the actual processes resulting in the observed year-to-year variability. This paper addresses these processes by linking Jarkus with ground-penetrating radar (GPR) and to meteorological observations. This approach has been applied to data from a non-nourished beach that has been subject to long-term net erosion and from an actively and frequently nourished beach that has experienced recent coastline progadation. The primary aims are to determine 1) the origin of sedimentary elements within the beach foredune area, 2) the fate of the sand volumes nourished in the past, and 3) the decadal-scale preservation potential of sand in the dune foot and on the adjacent backshore in light of the established nourishment policy. A secondary aim is to demonstrate temporal and spatial accretion and erosion variability along nourished coasts.

# 2 Study sites

The two study sites discussed in this paper are positioned along the west coast of the Netherlands, in a region where the coast is orientated roughly north-south (Fig. 1). The tidal range is about 2 m, with spring tide around 1.2 m above mean sea level (+ MSL). Prevailing winds, mostly moderate in strength, are from the southwest. Dominant winds, occasionally gale force or stronger, reach the coastline from south-westerly to north-westerly directions. Storm surges, with significant water-level set-up, accompany westerly to north-westerly storm-wind regimes. Water-level monitoring shows extremes of 3.50 to 3.85 m + MSL, with associated offshore significant wave heights of about 7 m.

## 2.1 Site 1. Non-nourished beach (Heemskerk aan Zee)

Long-shore redistribution of past nourishments has influenced any stretch of beach in one way or another, even when beaches and the adjacent shoreface have not been nourished themselves. This is the case for the Heemskerk site (Fig. 1). Nourishments were carried out just south of the study site in 1996/'97 and just north of the site in 2005. However, the first nourishment at the study site itself was not put into place until after completion of our study. In a situation of limited sediment availability, coastline retreat has taken place, resulting in narrowing and steepening of the foredune (Fig. 2) and, thus, in landward exceedence of the local RCL. Owing to the fact that no economically valuable built structures or infrastructure are present near the coastline at this site and that the total dune area is wide and high enough to ensure safety, this coastline recession has not been considered a problem to date. During and immediately after each storm surge event, erosion is taking place in the form of bluff formation and slumping, exposing older aeolian and storm-surge deposits that date from the 17$^{th}$ and 18$^{th}$ century (Cunningham et al., in prep; Bakker et al., in prep).
The coastline recession near Heemskerk aan Zee and the formation of large blowouts in the foredune are a consequence of the non-nourishment policy at this beach section and of the practice of dynamic preservation. It opens up the dune area for sand being blown inland from the present-day beach and the exposed foredune (see Fig. 2).

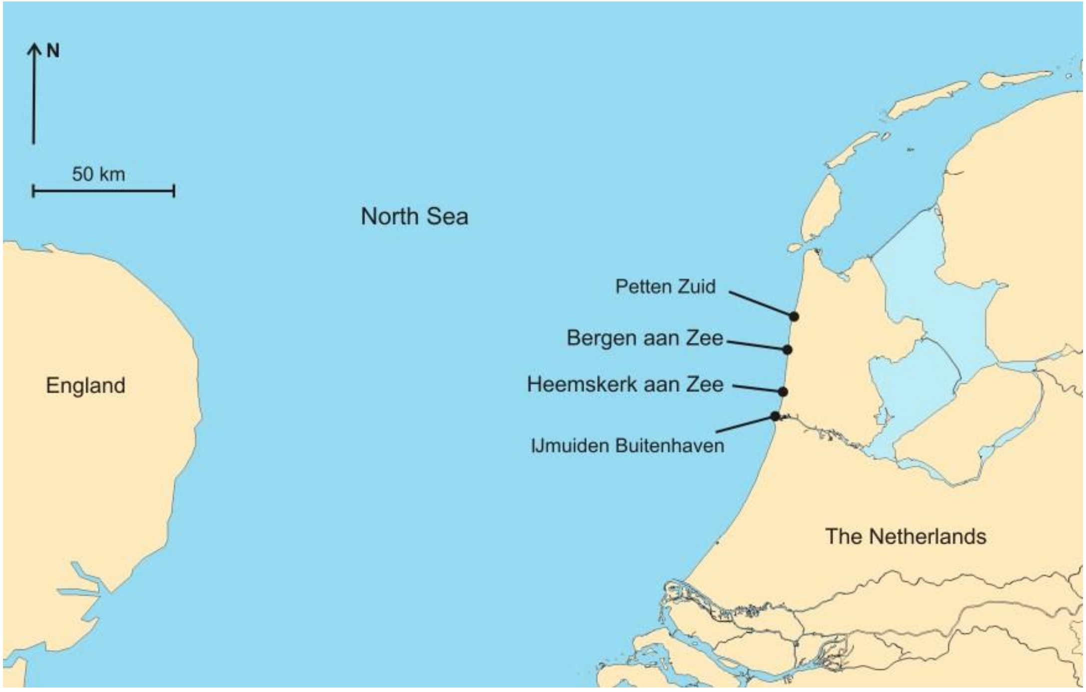


*Fig. 1. The study sites of Heemskerk and Bergen along the southern North Sea coast.*

*Fig. 2. Foredune near Heemskerk aan Zee (view to the north on Nov. 22nd, 2007). In the absence of nourishments, erosion has caused a steep, slumping foredune front that is subject to wind erosion and wave attack during water levels above 2 m +MSL. The back-dune drop has become over-steepened because of sand entrapment in the marram grass tussocks. Photo by Marcel A.J. Bakker.*

## 2.2 Site 2. Nourished beach (Bergen aan Zee)

The coastal resort of Bergen aan Zee (for location see Fig. 1) experienced strong and prolonged coastal erosion in the past. Twentieth-century aerial photographs of Bergen typically show a distinct escarpment along the foredune, most pronounced after the impact of storm surges (Fig. 4). The historical development of the coastline near Bergen is best demonstrated by a reconstruction of Schoorl (1990) showing the retreat of the coastline at Egmond aan Zee, a village about 5 km south of Bergen aan Zee (Fig. 3).
The storm surges of 1990 destroyed part of the Bergen aan Zee boulevard (Fig. 4). Sand nourishments were applied shortly after these erosional events. They include a large embankment (dune-face nourishment). Additional nourishments were put into place in 1992, 1995, 1997, 1999, 2000 and 2005 (see Table 1 for details). The nourishments prior to 2000 were carried out solely on the beach, whereas those of 2000 and 2005 were placed in part on the shoreface. Although the main goal of the nourishments is maintenance of the position of the coastline, they also result in a wider beach for the benefit of recreational activities.

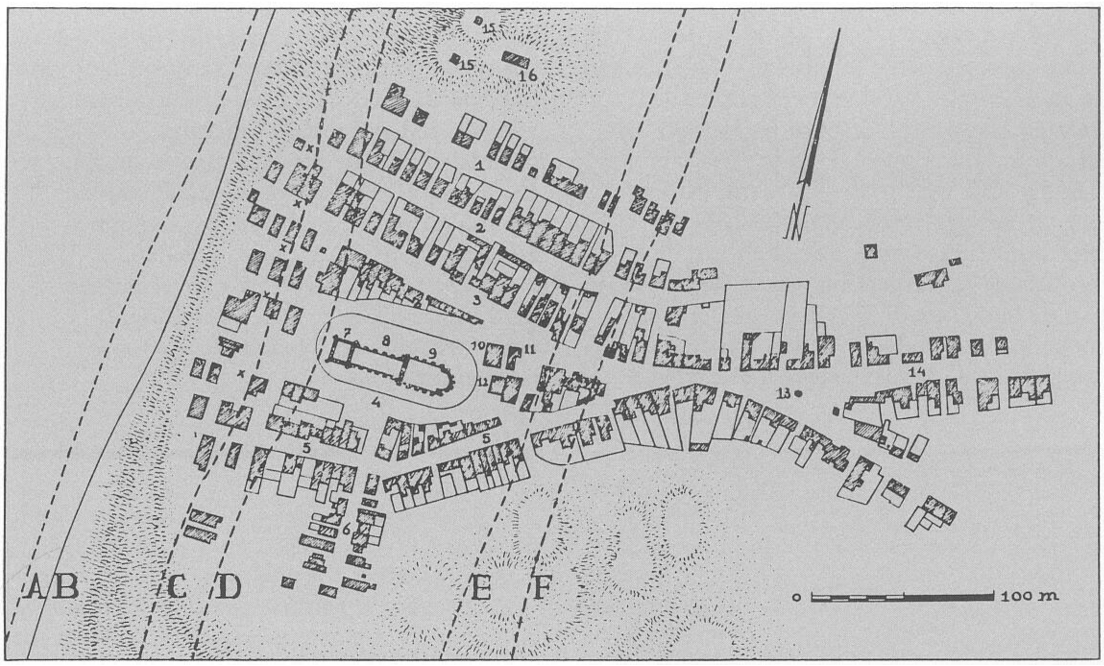


*Fig. 3. Coastline positions at Egmond aan Zee, from historical maps (Schoorl, 1990). A through F are the positions of the coastline in 1665, 1679, 1714, 1717, 1864 and 1940. The church (7,8,9) in the centre of the former town was destroyed during the storm surge of 1741.*

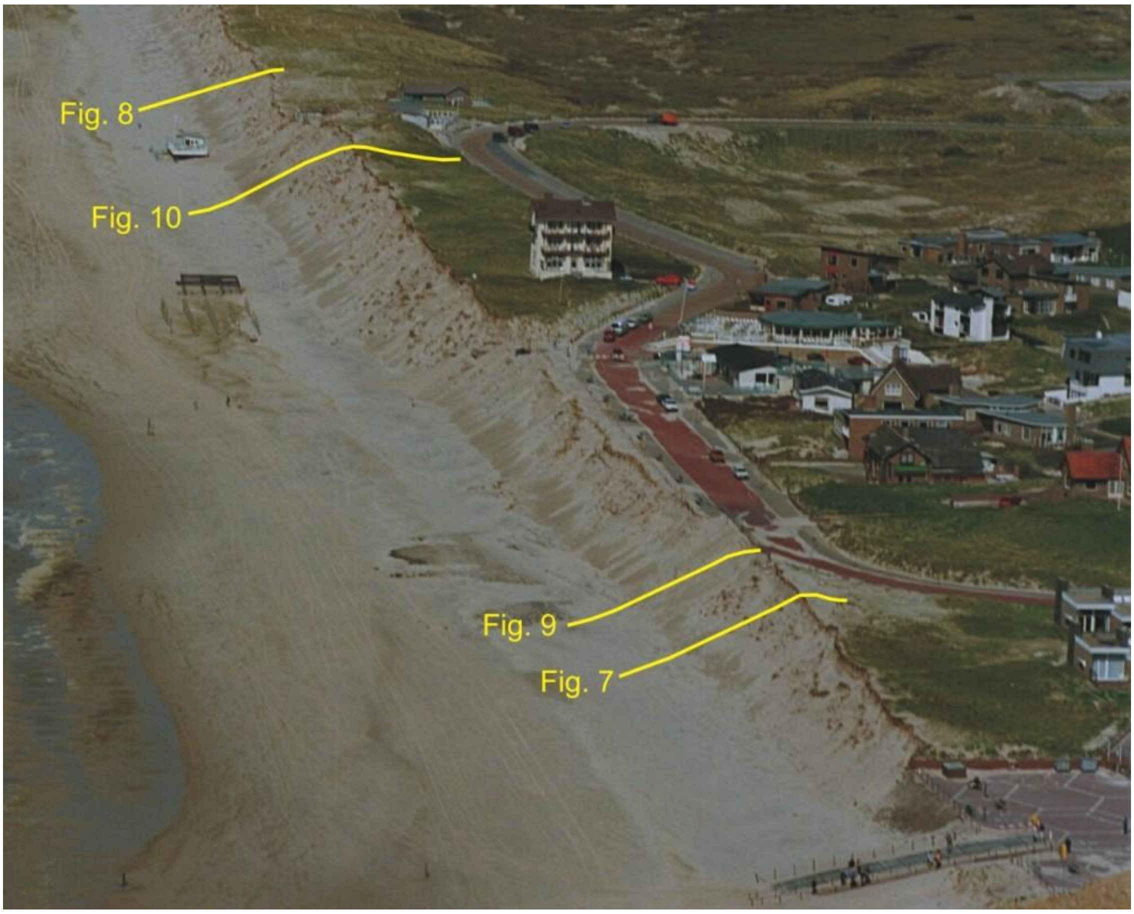


*Fig. 4. Oblique aerial photo of Bergen aan Zee looking north, taken shortly after the storm surges of 1990 (source: photo archive Rijkswaterstaat). Part of the boulevard was destroyed. At the beach, in front of the boulevard, Roman-age peat beds were exposed (dark coloured patches). The positions of images and cross-sections shown in Figures 7 to 10 are indicated; Jarkus transect 32.750 is represented by the line labelled Fig. 10.*

| Number | Type | Volume ($m^3$) | Volume ($m^3$/km) | Eleva-tion (m +MSL) | Date of place-ment | Date of Jarkus profiling in year of placement |
|---|---|---|---|---|---|---|
| 1a | Beach | 386,000 | 257,000 | | May-Jun 1990 | Apr 14th |
| 1b | Embankment | 60,000 | 40,000 | 6.00 | May-Jun 1990 | Apr 14th |
| 2 | Beach + embankment | 1,473,000 | 115,000 | 3.50 | May-Nov 1992 | Apr 25th |
| 3 | Beach | 101,000 | 168,000 | | Jun 1994 | Apr 25th |
| 4 | Beach | 306,000 | 306,000 | | May 1995 | Mar 30th |
| 5 | Beach | 352,000 | 144,000 | | Jun 1997 | May 22nd |
| 6 | Beach | 206,000 | 165,000 | | Apr-May 1999 | Apr 17th |
| 7a | Beach | 225,000 | 450,000 | | Jun 2000 | Nov 4th |
| 7b | Shoreface | 994,000 | 497,000 | - | Apr-Aug 2000 | Nov 4th |
| 8a | Beach + embankment | 300,000 | 200,000 | 3.75 | Apr 2005 | Apr 24th |
| 8b | Shoreface | 1,500,000 | 320,000 | - | Aug-Sep 2005 | Apr 24th |

Table 1. Overview of sand nourishments at Bergen aan Zee (source: Rijkswaterstaat, Waterdienst). Volumes are given both per kilometre (as an indicator of nourished sand in the kilometre bordering the study site) and per nourishment, as a typical nourishment extends along the coast for several kilometres. The maximum elevations (top surface) of embankments are given; the elevations of the beach nourishments are unknown. No nourishments were carried out in Bergen prior to 1990. Beach nourishment 3 (June 1994) was placed only along the southern part of Bergen aan Zee. Dates of Jarkus profiling refer to the onshore part of the monitoring.

# 3 Methodology

The research approach presented in this paper combines data from two main methodologies. The first of these focuses on data collection and interpretation of GPR transects perpendicular to the coast, over the foredune crest and into the area behind the frontal dune. GPR data were collected using PulseEkko PRO equipment (Sensors & Software Inc.), using unshielded 100 and 200 MHz antennae and 250 MHz shielded antennae.
GPR measures the time it takes for an electromagnetic signal to travel from the instrument to a reflecting layer in the subsurface and back (Fig. 5). The velocity of the radar signal in the sediment, needed to convert the measurements conducted in time to depth, was established by hand augering to particular reflecting features, by fitting to the depth of the groundwater table and by analysis of the shape of diffraction hyperbolae* analysis. Signal velocity in dune sand is strongly related to the water content (see e.g. Nielsen et al., 2009). The dry zone in the near-surface parts allows signal velocities of 0.11-0.12 m/ns. Within the first meter below the surface, the velocity typically drops to 0.07-0.08 m/ns.
Penetration depth is generally on the order of 12-15 m, depending on the depth of the groundwater table. In very steep terrain, signal losses limit the penetration depth.
In the processing of radar data, topographic correction is needed to get the right insights in the geometry and depth range of subsurface units. Position and elevation data were gathered by an RTK-GPS (real-time kinematic global positioning system) with cm-resolution.

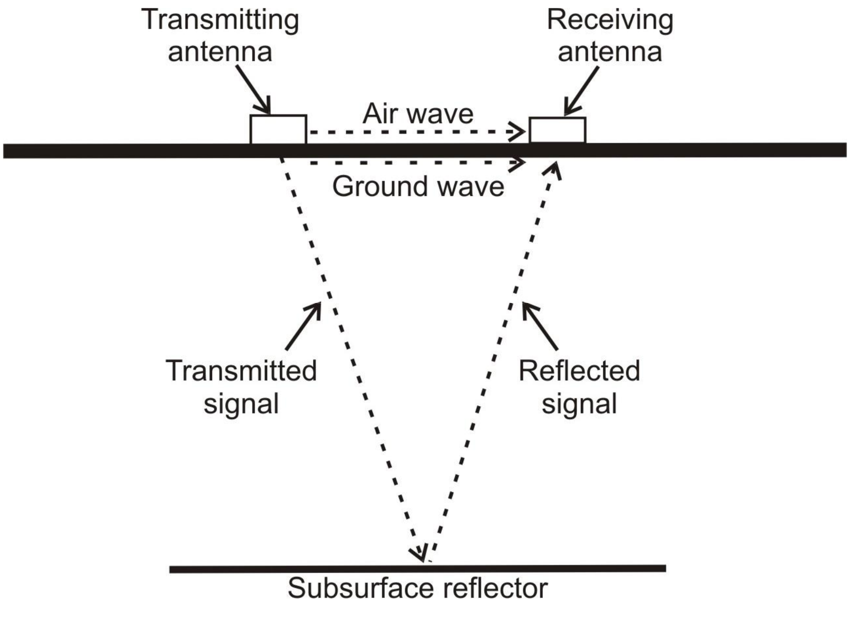


*Fig. 5. Principles of GPR. Subsurface features cause the transmitted signal to be reflected back to a receiver antenna. Movement of the antennas along transects makes it possible to image subsurface structures.*

After processing, the GPR images were interpreted on the basis of radar facies* identified on the profiles following the concepts of Van Heteren et al. (1998). Radar facies are defined as units of particular reflection properties (including magnitude and continuity) that differ from those of adjacent units. The units can encompass sedimentary bounding surfaces. The lithological characteristics of the radar facies were verified by hand augering. The radar facies are listed in Table 2, which includes a short description of their appearance, indications of their position and an environmental interpretation.

The second research methodology involves analysis of Jarkus coastal profiles through time, and comparison of the observed changes with the GPR images. Following this comparison, the observations are linked to processes - driven by mostly meteorological conditions - that are known to have an impact on sand-nourished beach-foredune environments.

# 4 Results

## 4.1 Site 1. Non-nourished beach (Heemskerk aan Zee)

*GPR surveying*

A steep dune scarp that was the result of a significant storm surge in November 2007 creating a local water level of 3,13 m +MSL provided a (laterally discontinuous) exposure of older beach- and aeolian sediments (Van Heteren et al., 2008). Over a length of about 1 km, between RSP (beach pole) 48.500 and 49.650 km, relatively coarse-grained palaeostorm-surge deposits were exposed at various elevations, intercalated with wind-blown sand. At RSP 49.500 km near Heemskerk aan Zee, the foredune scarp was partly cut into a large blow-out in the frontal dune, enabling access for GPR surveying on top of the exposed sequence. This enabled direct comparison between the GPR images and exposed strata. The exposures were used to ground-truth the corresponding GPR images, linking subsurface reflections and reflection configurations (facies*) with exposed boundaries and strata. This data set was used to interpret all other GPR transects.

GPR profiles were measured perpendicular to the escarpment, starting at the scarp and extending across the steep foredune, to a maximum elevation of 18.5 m +MSL, and landward down into the adjacent blowouts with lowest points around 3 m +MSL. The seaward side of the foredune is dominated by bare sand, and was temporarily oversteepened as a result of the scarp formation. GPR profiling over slumped (i.e. disturbed) units was avoided as much as possible. The vegetated lee side of the foredune is particularly steep, with angles up to 37° (Fig. 2). The steep slope reflects strong fixation by European marram grass (*Ammophila arenaria*).

The steep sections of the GPR transects are characterized by poor signal penetration, attributed to the inclined position of the transducers relative to the stratification. This unfavourable position leads to reflection of the signals away from the receiver antenna.

Radar facies at the lee sides are dominated by subparallel, inclined reflection sets (facies FDL, Table 2, Fig. 6 in yellow). This unit is interpreted as an aeolian deposit in the densely vegetated wind shadow of the migrating foredune, at calculated angles up to the aforementioned 37°. Local diffractions are caused by debris that has washed up on the shore and has been transported farther inland by storm winds.

The shell-bearing beds are expressed on the GPR images as very strong, continuous and subparallel reflection sets (facies SB, Table 2, Fig. 6 indicated in red). Hand augering at the landward dune foot confirmed the lateral, landward continuation of this unit, as seen on the GPR. Below this unit the groundwater table is visible as a continuous subhorizontal reflection at ~1.5 m +MSL (facies WT, Table 2, Fig. 6 in blue). Beneath this reflection, GPR facies are rather transparent, which is attributed to the brackish character of the groundwater at this coastal setting (cf. Benneth et al., 2009).

Inclined and listric* (spoon-shaped) reflections present above unit SB are attributed to aeolian bounding surfaces within the foredune (facies FDC).

*Jarkus analysis and comparison with GPR imaging*

Jarkus profiles from selected years demonstrate a distinct landward shift of both the seaward foredune foot and the foredune crest, and a general oversteepening and narrowing of the foredune. Over the period 1965-2008 the dune crest has migrated ~0.5 m/yr and the dune

foot (beach side) ~1.0 m/yr. It is interesting to note that the dune crest remained more or less on the same topographical level (Fig. 6).
This ongoing recession in combination with large blow-out formation is the consequence of the non-nourishment policy at this beach section, and of the practice of dynamic preservation. The result is a coastline with high morpho- and biodiversity.

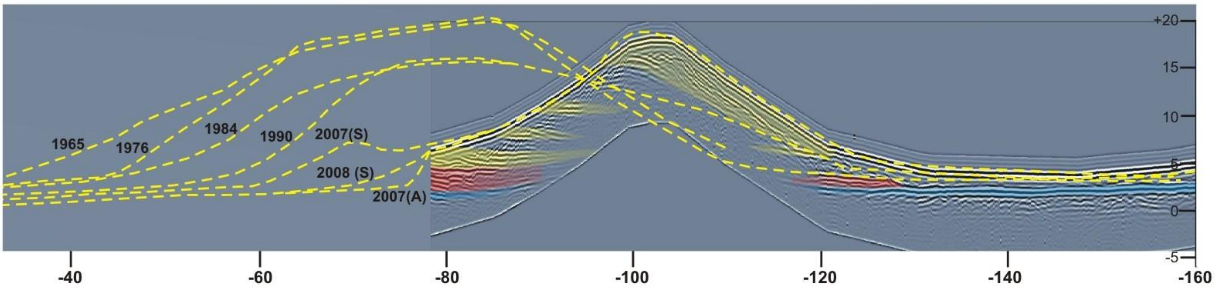


*Fig. 6. Combined image of GPR profile (200 MHz, unshielded) across the foredune at RSP(beach pole) 49.500 near Heemskerk aan Zee and the corresponding Jarkus profiles from selected years. Profiles marked S are standard Jarkus profiles recorded in spring, the profile marked A is recorded with RTK-GPS shortly after the storm surge of Nov. 2007.The dune crest has migrated ~0.5 m/yr and the dune foot (beach side) ~1.0 m/yr, resulting in narrowing and oversteepening of the foredune. The groundwater table (in blue) and historical storm surge beds (in red) are imaged by the GPR profile. A set of strong and inclined subparallel reflections is visible at the landward side of the profile.*

### 4.2 Site 2. Nourished beach (Bergen aan Zee)

*GPR Surveying*

Four GPR transects collected on the intensely nourished beach/foredune system of Bergen aan Zee show a complex nourishment history. The positions of these transects are shown in Fig. 4, which shows a prominent scarp following a 1990 storm surge. The vastly different present-day situation is clearly visible in Fig. 7: a generally gentle seaward slope covered with marram grass. The remains of the 1990 scarp can still be recognized locally as a morphological break in the slope. Near the base of the current slope, scarcely vegetated, ephemeral dune hillocks are present. The GPR data show shore-perpendicular transects from the dune foot over the gentle slopes toward the hinterland in the immediate vicinity of the Jarkus profile at RSP 32.750 km (situated in the northern part of the town).


*Fig. 7. Situation at Bergen aan Zee in October 2007. The former position of the 1990 scarp is indicated in red, along with the position of the GPR profile (in yellow) shown in Fig. 8. Most striking is the gentle slope from the former scarp toward the present-day foredune foot. Photo by Marcel A.J. Bakker.*

| Unit | Facies description | Position | Interpretation |
|---|---|---|---|
| WBN | Long, subparallel reflections, dipping seaward; erosive lower boundaries; diffractions | On beach against foredune and embankment | Wind-blown (nourishment) sand, brown, diffractions due to modern waste incorporated in the sand |
| WBS | Long, subparallel reflections, dipping seaward; erosive lower boundaries | On beach against foredune and embankments | Wind-blown, white, fine-grained sand |
| EM | Strong, subparallel reflections | Against former scarp, below unit WBN | Embankment |
| FDC | Subparallel, landward-dipping reflections; bounding surfaces; diffractions* | | Foredune core, diffractions due to root concentrations (marram grass) and debris (in top part only) |
| FDL | Steeply dipping, subparallel, local diffractions | On lee side of foredune | ‘Avalanche’ deposits of drifting wind-blown sand, diffractions due to modern waste |
| TR | Mostly transparent facies; blanket | At the surface behind foredune | ‘Fall-out’ of wind-blown sand, derived from beach (nourishments) and from exposed foredune scarps |
| SB | Very strong, continuous and subparallel reflection | About 2 m +MSL | Shell-bearing storm surge beds |
| WT | Subhorizontal, single reflection | From 1-2 m +MSL | Groundwater table |
| P | Tabular top-and-bottom reflection set; horizontal; transparent | Near MSL/groundwater table | Peat beds |
| PF | Westward-dipping low-angle reflections, locally hummocky | Inland, between 0.5 and 2 m –MSL. | Progradational upper-(storm) beach deposits, local aeolian deflation and infilling |

Table 2. Overview of radar facies visible on GPR profiles of beach and foredune deposits at Heemskerk and Bergen aan Zee.

Fig. 8 presents a 100-MHz transect from the dune foot over the foredune crest (see Fig. 4 for location). At ~ 1.0-2.0 m +MSL the groundwater table is visible (unit WT, Table 2). On the seaward side, it is situated near the top of westward-dipping, low-angle oblique reflections, interpreted as progradational beach deposits (unit PF, Table 2). Farther landward, the water-table reflection is masked by a set of high-amplitude reflections (unit P), marking top and bottom of remnants of a peat bed that were exposed on the beach after the storm surges of 1990 (Fig. 4).
Farthest inland, subparallel, mostly landward-dipping reflection sets and bounding surfaces (unit FDC) occur above the water table. Diffractions are present mostly in the top part of the unit. This reflection configuration is interpreted as the original foredune. The diffractions are attributed to marram grass roots and to buried debris (the latter mostly in the top parts). This unit can also be recognized in Figures 9 and 10.
Unit FDC is generally bounded on its seaward side by a sharp, seaward-dipping discontinuity at angles of about 32°. This erosional boundary is commonly characterized by a continuous reflection that is caused by a marked change in lithological and sedimentological properties. It represents the 1990 scarp (compare with the recent Heemskerk aan Zee situation) that is buried in the present-day foredune. Locally, the reflection terminates at the position of a morphological break in the seaward slope of the foredune. The reflection marking the scarp may be unclear because of slumping of the steep slope during and following the 1990 storm surges. Additionally, the scarp may be accompanied by secondary slide planes within the foredune sand body. These slide planes are created under storm-wave attack, when entire blocks of dune sand, held together by marram grass, slide into the surfzone as the steep-sided dunes are undermined.
The discontinuity is now covered with several sedimentary units resting on top of the scarp. On the GPR profiles, these units are recognised by a dominance of long, subparallel reflection sets, dipping seaward and exhibiting erosive lower internal boundaries. Locally, diffractions are present.
Situated against the base of the discontinuity, unit EM (Table 2) shows strong subparallel reflections across a limited lateral distance. Hand augering in this unit turned out to be very difficult because of the presence of very dense compacted (sub)angular brown sands that contain abundant shells (mostly *Donax*) and shell fragments. Unit EM is interpreted as the remains of the embankment, or dune-face nourishment, that was put up as a quick fix to repair the storm-surge damage of 1990. Hand augering has proven two overlying units to be aeolian in origin (judging from the well-sorted character of the uncompacted sand, and marked by the presence of wind-blown debris). Patchy unit WBS (Table 2) is composed of fine subrounded white-yellow sands whereas unit WBN consists of subangular brown sand. The white-yellow and brown wind-blown sand assemblies produce identical radar facies.
Analysis of the GPR profile shows that - at this location - the net accumulation of post-1990 sand adds up to $190m^3/m$. The toe on the North Sea side of the foredune has migrated seaward over some 18 m over the period 2000-2008.

The natural foredune core (unit FDC) is composed of white-yellow, fine-grained sands of Baltic (northern) origin poor in or devoid of $CaCO_3$, whereas the nourished sands (units WBN and EM) are generally brown, angular, rich in $CaCO_3$ and coarse grained of Rhine provenance (Eisma, 1968; Stuyfzand et al., 2010). South of Bergen aan Zee (hence also at Heemskerk aan Zee) these brown sands also occur in the natural foredune. At Bergen aan Zee, marine sands of southern origin are introduced in a coastal system consisting of northern sand. The pockets of the wind-blown unit WBS (or slumps from the foredune) in Fig. 8 are the last relicts of a foreshore-beach-dune system composed of white-yellow sand. Presently the beach-dune system at Bergen aan Zee is saturated with brown sands of Rhine provenance. Their high $CaCO_3$ content will inevitably lead to rapid changes in dune vegetation in and around the resort of Bergen aan Zee, as geochemical and lithological characteristics of the soil are already subjected to change (Stuyfzand et al., 2010).

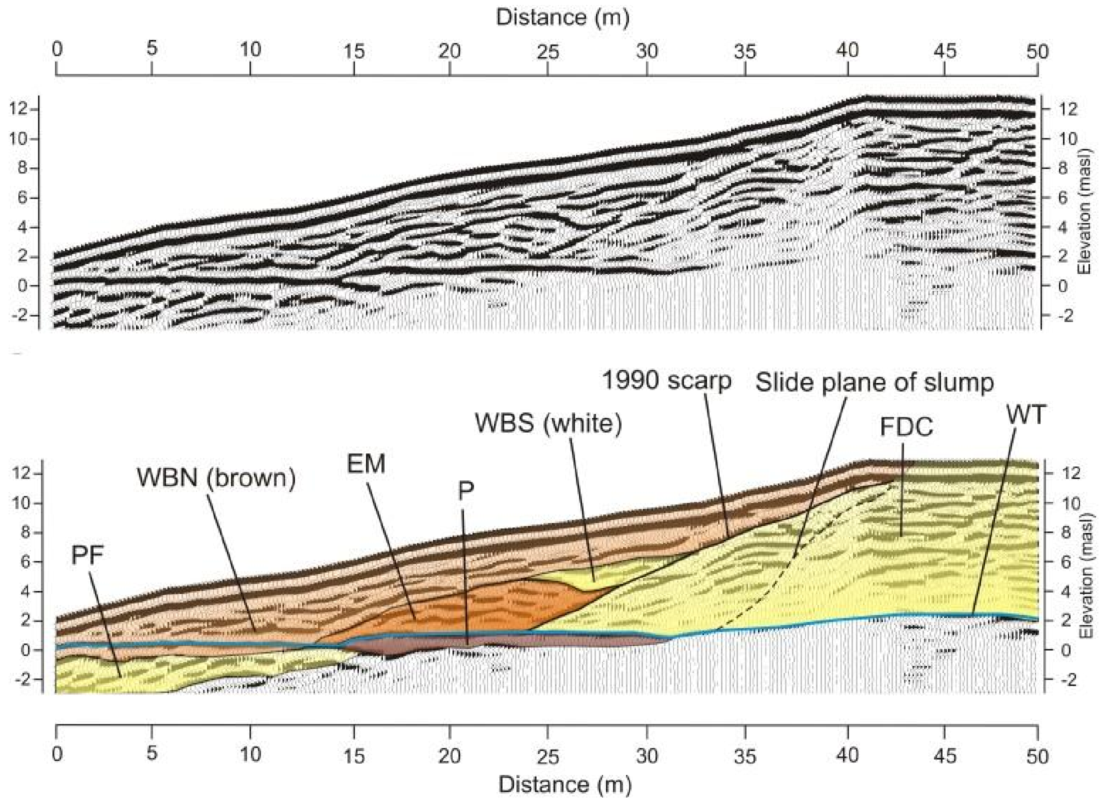


*Fig. 8. 100-MHz GPR section at RSP 33.160 km, fronting Bergen aan Zee (see Fig. 4). Seaward part is to the left. Several GPR facies are distinguished (see Table 2).The net volume of post-1990 units is 190m$^3$/m. This added sand has resulted in an 18-m seaward shift of the foredune toe.*

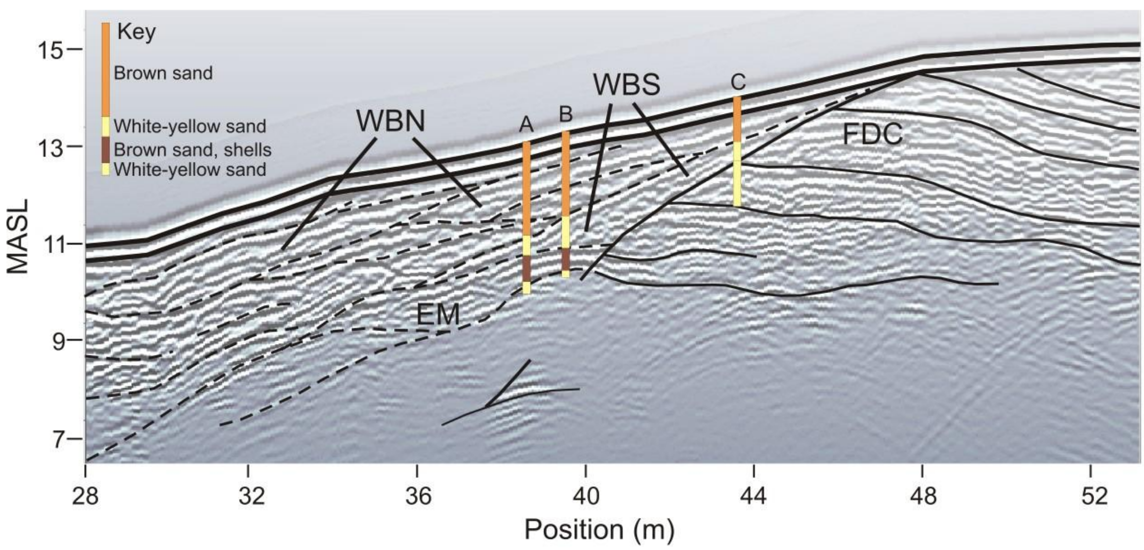


*Fig. 9. Detail of a 250-MHz GPR section at RSP 32.630 km (see Fig. 4), with borehole data (A, B & C) identifying radar facies SH, WBS, WBN and FDC.*

The facies succession discussed above is also visible on additional GPR profiles such as the one shown in Fig. 9. Hand-augered cores were used to assign lithological characteristics to GPR facies EM, WBS, WBN and FDC. The same sequence as presented in Fig. 8 is present: an embankment (EM) resting against the scarp, topped by wind-blown white sands (WBS) and wind-blown brown sands (WBN).

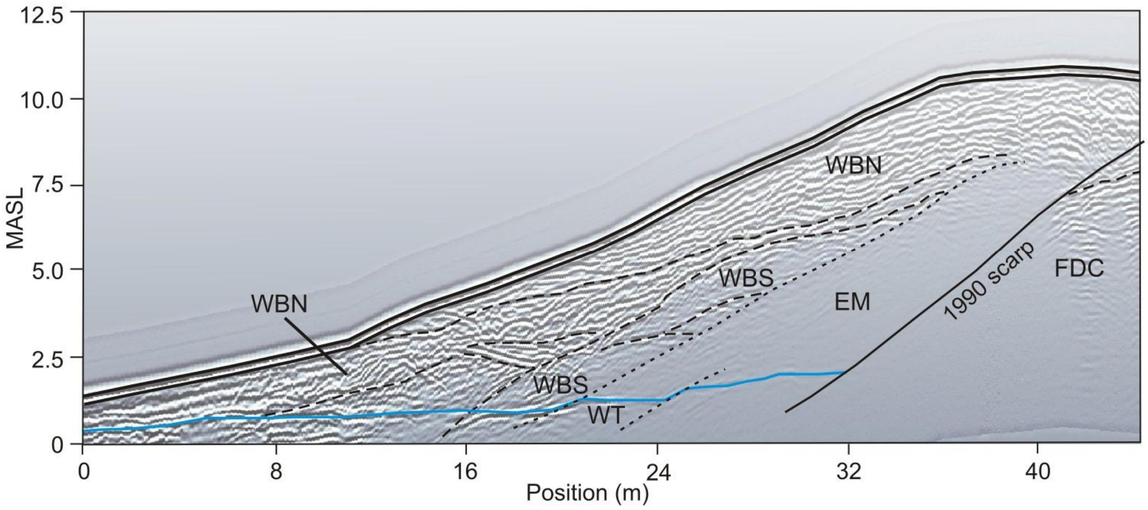


*Fig. 10. 250-MHz GPR section III at RSP 33.110 km (see Fig. 4). The inner transparent part is an embankment. The volume of net accumulation after 1990 is 180 $m^3$/m. This added sand has resulted in a 30-m seaward shift of the foredune toe in the period 1990-2008.*

Fig. 10, a GPR profile at position RSP 33.110 km (50 m south of the profile depicted in Fig. 8) depicts both the 1990 scarp (solid black line) and steps in the groundwater table (solid blue line). These steps coincide with boundaries between subunits within radar facies WBN, WBS and EM (delimited by dashed lines). The steps in the groundwater table can be explained by slight changes in grain-size distribution and associated capillary properties. The net volume of post-1990 sand is 180 $m^3$/m. This added sand has resulted in a 30-m seaward shift of the foredune toe in the period 1990-2008.

In analogy to the Heemskerk situation, nourishment sand has been redistributed by wind. ‘Fall-out’ of wind-transported nourishment sand behind the foredune crest has formed a blanket of sediment on top of the original dune sediments (unit FDL, not shown on the GPR images). This allochthonous sand can clearly be distinguished from the autochthonous sand by their color (brownish *vs*. yellow-white) and grain size medium coarse vs. medium fine). As a result of wind redistribution of nourishment sand, changes in dune vegetation increasingly extend beyond the actual nourishment locations. The vegetation reacts to changes in mineralogy and in lime content (cf. Stuyfzand et al., 2010).

*Jarkus analysis and comparison with GPR imaging*

The Bergen aan Zee GPR profiles are situated close to Jarkus transect 32.750 km. Yearly data of this transect are available over the period 1965-present. Most profiling of the dry part, relevant in the present study, is done in spring. Beach nourishment will usually take place during the summer months, after the annual Jarkus profiling. In 2000, however, measurements were taken on November 4th, after the large shoreface and beach nourishment in the same year (Table 1).

When all Jarkus profiles of a selected location are analysed, it is possible to visualise stacked sediment volumes (deposited in different years) making up the sand wedge that has accumulated in front of the 1990 scarp. Fig. 11 shows that this sand wedge is composed of sand volumes from only a small number of years. The Jarkus data were collected each spring, with the exception of 2000, when data were collected in November and 2002 (no Jarkus data available; profile established by interpolation between 2001 and 2003). The 1990 profile represents the most inland position of the recorded period. All subsequent profiles are positioned westward (i.e. at a higher position) relative to the 1990 line, with exception of the western part of the 1993 profile. Even though the profiles in the period 1990-1999 were positioned seaward of the 1990 line, only sediment deposited in front of the scarp in 1990/91 has survived one or more erosive events that took place before the Jarkus profiling of November 4th, 2000. In the period 2000 – 2008 gradual accumulation has pushed the profile seaward. Sand nourishments were conducted in 2000 and 2005 only, but all other years have contributed to the sand wedge that fronts the 1990 scarp.

Fig. 12 shows the data of Fig. 11 in numerical form (between -90 and -145 m). Sediments from 1992 and the period 1994 to 1999 have not been preserved at Jarkus transect 32.750. The largest volumes that make up the sand wedge fronting the scarp originate from 1991 (the 1990 post-storm embankment), 1993 and 2000 (the large nourishment). After 2000, gradual accumulation has taken place. This accumulation is a result of the redistribution by wind of nourishment sand located on the dry beach, as evidenced by field observations, GPR reflection configurations, and sedimentology of hand-augered material.

Analysis of year-to-year gross volumetric changes at Jarkus transect 32.750 provides important additional information on system morphodynamics (Fig. 13). Indicated are net changes for each year in the period 1990-2008, compared to the previous year, of the higher part of the beach plus the foredune front (between -90 and -145 m in Fig. 11). Erosion occurred primarily in 1990, 1992 and 1999, while large accumulation occurred not only in 1991 (the 1990 post-storm fix) and 2000 (the largest nourishment to date), but also in 1996 (2nd largest beach nourishment to date).

According to the Jarkus data at transect 32.750, there is an overall net growth of 233 $m^3$/m over the period 1990-2008, 21 % of which originates from the 1990/91 embankments, 11 % from 1993, 36 % from the 2000 nourishments and the remaining 32 % from the period 2001-2008. The addition of sand has resulted in a seaward shift of the foredune toe of about 35 m.

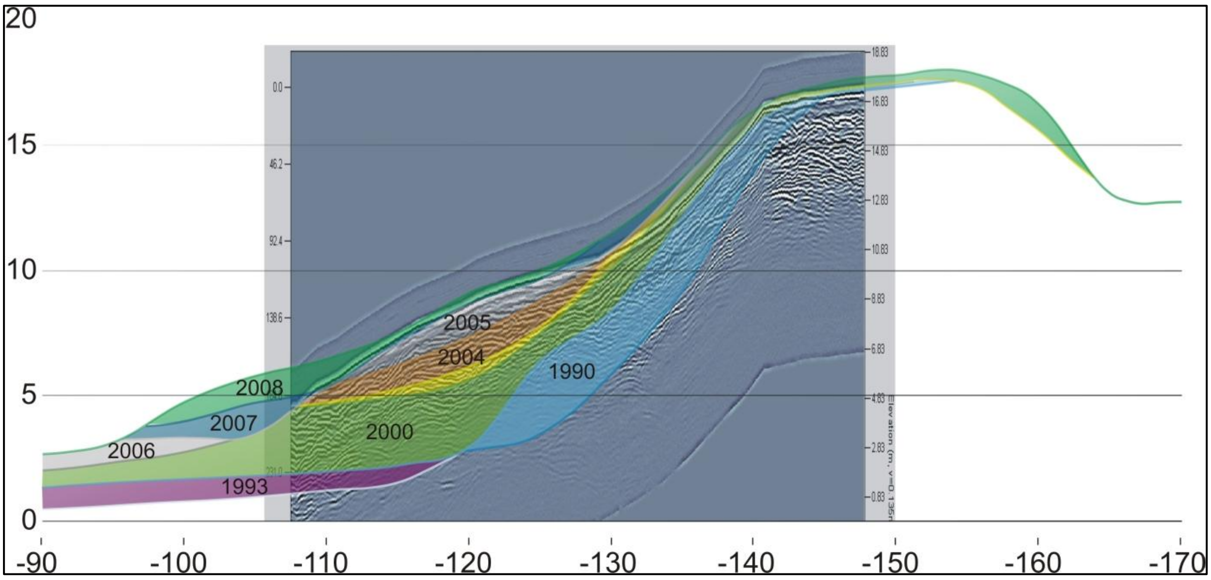


*Fig. 11. Analysis of Jarkus profiles for transect RSP 32.750 km, plotted over 250-GPR profile from the same position. Preserved sand volumes originating from different years are shown in different colours (situation 2008). See also Fig. 12 & 13. The largest volumes that are present originate from 1990/91 and 2000. In the period 2000-2007 no significant storm surges occurred (see Fig. 14). The resulting absence of major erosive events allowed wind-blown sand to accumulate gradually against the lower half of the foredune.*

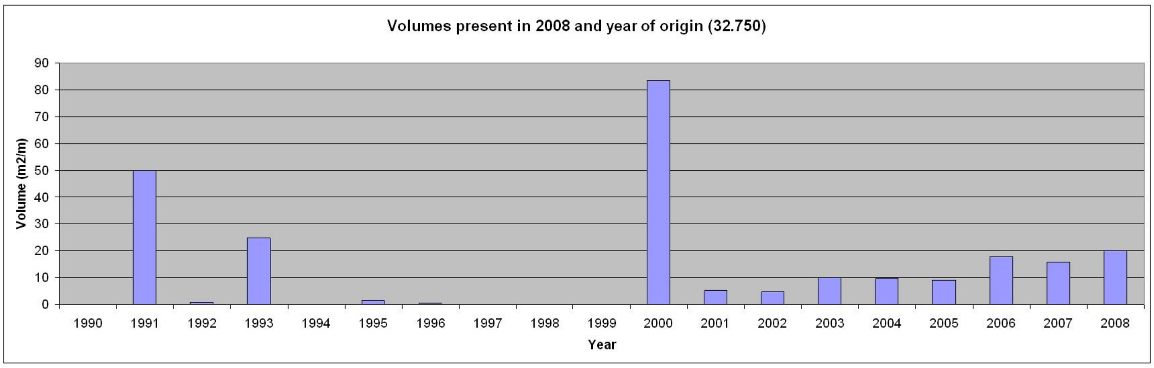


*Fig. 12. Post-1990 sand volumes present in 2008, and their year of origin at Jarkus transect 32.750. About 233 m³/m sand has accumulated since 1990.*

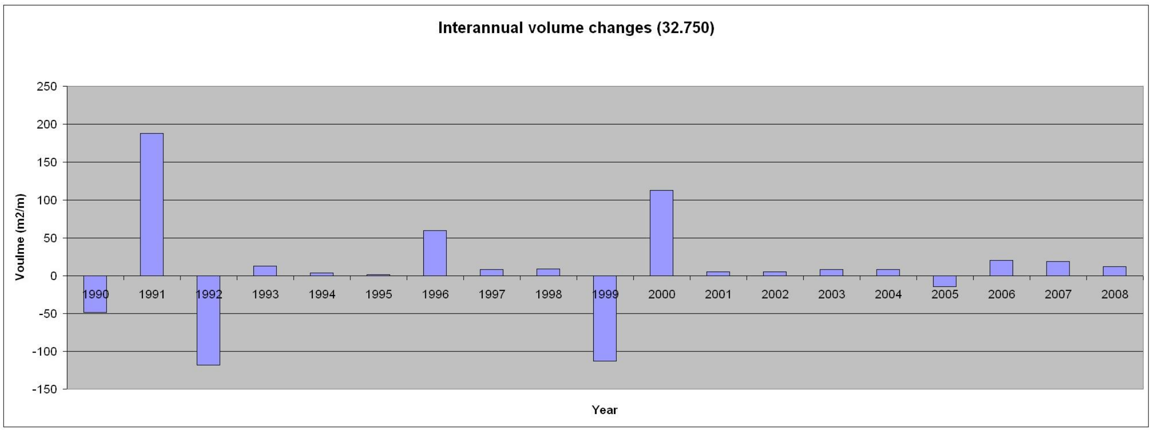


*Fig. 13. Sediment dynamics at Jarkus transect 32.750. Indicated are interannual volume changes. Profiles from subsequent years are compared to calculate volumes of erosion or sedimentation.*

### 4.3 Understanding processes reworking beach nourishments

It is relatively easy to determine the geometry, composition (origin) and age of nourishment-related sand deposits at the upper parts of the Bergen aan Zee beach and the adjacent, windward part of the foredune. Linking these observations to actual processes in the coastal environment is more difficult. Abundant studies have shown how coastal processes act on beach sand; i.e. on the effect of aeolian sand transport (e.g. Van der Wal (2004) for aeolian sand transport and Pool (2009) and Roelvink et al. (2009) for wave-induced erosion and associated processes). A complete understanding of the impact that these processes have on the coastal profile also requires inclusion of meteorological and marine observations from the time period under consideration.

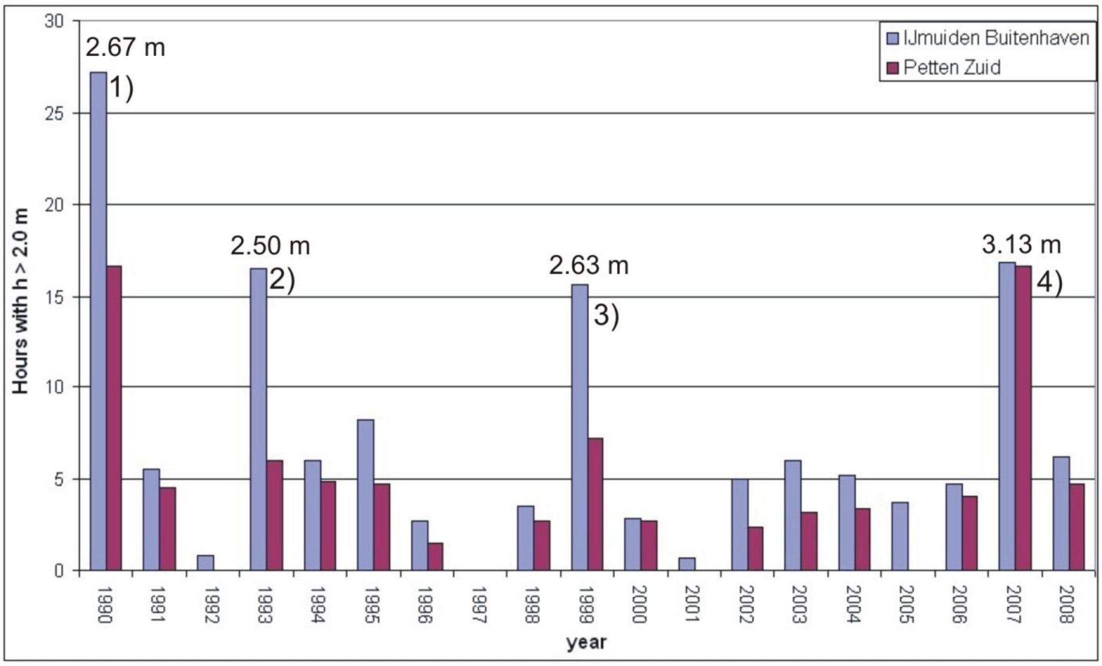


*Fig. 14. Duration (in hours) of water levels above 2.00 m +MSL for each year in the period 1990-2008, in Petten Zuid (north of the study areas) and IJmuiden Buitenhaven (south of the study areas, see Fig. 1). Average high-water level at these locations is 0.80 (1.05) and 0.95 (1.25) m +MSL, respectively (maximum spring-tide levels in brackets). Highest levels are usually reached at IJmuiden. Significant storm surges occurred in 1990, 1993, 1999 and 2007. The maximum water levels observed during these extreme events are indicated above the bars in the graph (in m +MSL).*

The duration of water levels above 2 m +MSL for each year in the period 1989-2008 at Petten Zuid and IJmuiden Buitenhaven (see Fig. 1) is a relevant parameter in understanding the impact of waves on the coastal profiles of Heemskerk aan Zee and Bergen aan Zee. Although the exact water level at the dune foot is determined in part by beach profile and breaker-bar geometry, which affect wave run-up, the 2 m +MSL water level as measured at the two monitoring stations is a practical indicator for the threshold that needs to be reached at both study sites before waves can erode the dry beach and foredune.
Water levels above 2.0 m +MSL are reached only during significant storm surges; the normal spring high-tide level is around 1.05 +MSL (Petten) and 1.25 +MSL (IJmuiden). The maximum levels reached during 1990-2008 at IJmuiden Buitenhaven were 2.67 m +MSL in

1990 and 3.13 m +MSL in 2007. The highest level recorded within the instrumental monitoring time series is 3.85 m +MSL in 1953. Aside from the surge-related water levels, wave run-up has to be taken into account. Under specific conditions, wave run-up can reach elevations of more than 4-5 m +MSL (Pool, 2009).
Storm surge period 1, as shown in Fig. 14, occurred in 1990 and caused the damage shown in Fig. 4, creating the most landward coastal profile to date. Storm surge 2, in 1993, eroded the beach to even lower levels than 1990, but the embankments constructed in 1990 protected the dune foot and stayed mostly intact. The 1999 storm surges (3 in Fig. 14) eroded all sediment accumulated between 1993 and 1999, including the beach nourishments of 1994, 1995 and 1997. Storm surge 4, in November 2007, resulted in the highest water levels since 1976, but had little impact on the profile at Bergen aan Zee (see next section).

The erosive effects of the storm surges, as indicated in the volumetric balances of Fig. 12, are more than offset by the sand-accumulation effects resulting from the nourishments. In 2000, the largest beach nourishment to date was carried out. An even larger shoreface nourishment was put in place around the same time. A 7-year period of marked meteorological calmness followed; water levels above 2.0 m +MSL were very rare and short-lived. Despite the fact that coastal erosion was limited during this time, additional beach (including embankment) and foreshore nourishments were carried out in 2005. As a result of the period devoid of significant storm surges, and reinforced by the 2005 nourishment that provided a new source of sediment, aeolian sand accumulation against the foredune has occurred ever since the year 2000, without any significant intermittent erosion.

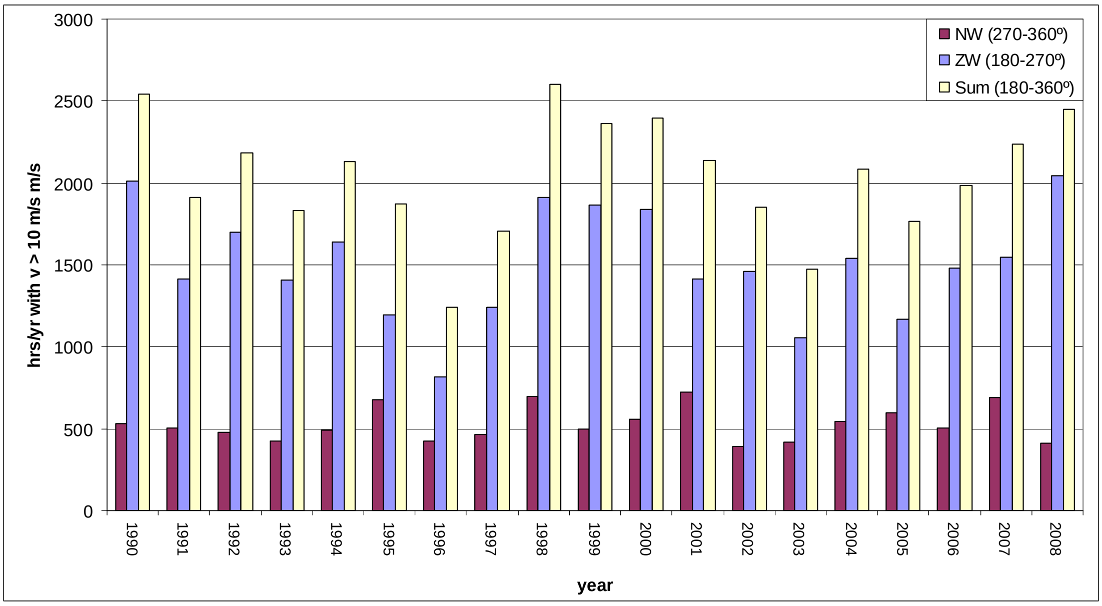


*Fig. 15. Duration (in hours) of wind speeds >10 m/s for southwest and northwest circulations (and their sum) in the period 1990-2008 (wind directions indicated). Data from IJmuiden. Most hours with potential sand transport occur in 1990, 1998-2000 and 2008. Calm years are 1996 and 2003. Note that windy years do not necessarily coincide with storm-surge years (cf. Fig 14).*

Next to waves and currents, wind is the third important parameter affecting erosion, transport and deposition in beach environments. Shore-parallel sediment transport prevails during periods of strong southerly to southwesterly winds. Vast amounts of sand are set in motion

under these conditions. Inland sand transport occurs mostly when strong westerly winds blow perpendicular to the coast.
Fig. 15 shows wind frequencies for the period 1990-2008 at IJmuiden. Indicated are hours with wind speeds above 10 m/s, which are assumed to have potential sand-transporting capacity when acting on typical western Netherlands beach sediment. For natural and nourished sands with non-uniform grain sizes, critical wind velocity is not a single value but a threshold range (cf. Nickling, 1988). The threshold value for the Bergen aan Zee situation gives the upper value of the critical range, and is a function of grain-size distribution of the local (nourished) beach sediment (cf. Van der Wal, 1998). The frequencies in Fig. 15 are provided for winds from the 180-270º quadrant (shore-parallel sediment transport dominant), the 270-360º quadrant (inland sediment transport dominant) and their sum (180-360º). Easterly winds are not considered as these are rare and do not usually reach 10 m/s. Even when strong easterly winds occur, (seaward) sediment transport is limited by vegetation at the landward side of the foredune.
Potential sand transport occurs during 2,000 hours (i.e. more than 80 full days) in an average year. Two exceptionally calm years were 1996 and 2003. Windy or calm years do not necessarily coincide with storm-surge years. Although no direct links with the observed interannual profile changes can be established, it is clear that given sediment availability on the dry beach and in non-vegetated foredune parts, redistribution of sand by wind will be significant almost every year.

## 4.4 Storm-surge field observations

During the storm surge of November 2007 field observations were conducted in both Heemskerk and Bergen aan Zee. Along the Dutch coast, the north-westerly storm winds were not extreme by themselves (8-9 Bft). Nevertheless, the highest water levels since 1976 were recorded. The height of the storm surge was determined in the northern part of the North Sea, far offshore, where hurricane-force winds associated with a slow-moving depression were active across an extremely long fetch. These conditions generated high waves that moved into the southern part of the North Sea before reaching the coastline (maximum wave heights of 7-8 m near IJmuiden).
During high tide, the water easily reached the dune foot, saturating the sand. Waves attacking the dune front resulted in large-scale scarp formation. In general the dune foot was eroded back between 2-3 (typical value for Bergen aan Zee) and 10 m (maximum value for Heemskerk). The amount of erosion varied along the coast, depending on the presence or absence of nourishment sand, nearshore bathymetry, height and width of the beach, and other local conditions (e.g. Houser et al., 2008; Pool, 2009 & Brodie & McNinch, in review).

In Heemskerk, the scarped dune face formed fresh exposures of foredune sand with intercalated shell-bearing storm-surge deposits. In Bergen aan Zee, water-lain beach-nourishment sands (including embankments) could be recognized in fresh exposures as generally subhorizontally stratified, densely packed sandy sediments. The water-lain nourishment sands are subangular and poorly sorted, and marked by silty admixtures, shell concentrations and local clay balls. They also contain plastic, rope and other types of anthropogenic debris.
The subangular nature and dense packing of these sands makes them more resistant against erosion than the loosely packed, well-rounded aeolian sands. This increased resistance may explain part of the observed difference in dune-foot erosion between Heemskerk and Bergen aan Zee. It reduces slumping, which takes place at relatively steep angles. Aeolian strata are

more easily washed away and slump at considerably gentler angles. An additional explanation for the difference in dune-foot erosion is the high elevation of the pre-storm beach at Bergen aan Zee (Fig. 11).
Type and composition of nourished sediment and the way it is introduced in the beach system are important elements in the longevity of beach nourishments.

*Fig. 16. Scarp formation in water-lain beach-nourishment sand near Bergen aan Zee during the storm surge of November 9th, 2007.Photo by Marcel A.J. Bakker.*

# 5 Discussion

Although the two sites analysed as part of this study represent both a nourished and a non-nourished stretch of coast, our results must be validated by observations from other locations. A regional study of foredune behaviour in the Netherlands was recently completed by Arens et al. (2010) using laser-altimetric data and Jarkus profiling. To quantify the effects of the nourishment policy on the dunes, they analysed total volumetric changes of the frontal dune along the entire Dutch coast. They conclude that, in general, sand accretion to the frontal dunes has increased since the establishment of the nourishment policy. Analysis of data just south of Bergen aan Zee (between RSP 34 and 37 km, 1 to 4 km south of the GPR transects) shows a trend break around 1997, from net erosion to net volumetric growth. For RSP 49.500 in the Heemskerk area they also observed a change around 1997, from a net strong erosional state to a more or less stable foredune volume. At this location a landward shift of the dune foot coincides with volumetric growth at the landward side of the fore dune, as confirmed and imaged by our study (fig. 6).
Arens et al. (2010) see the observed volumetric trend breaks as an indirect proof of accretion following the implementation of the nourishment policy. Direct proof is hampered by local effects, such as sand bar migration, blowout formation and – in general terms – a decrease of storminess after 1990. This study shows that the latter is true for storm surges, but not for stronger winds in general (fig. 15).

The coastline recession near Heemskerk aan Zee that occurred during recent years is a consequence of the non-nourishment policy at this coastal section, and more generally of dynamic coastal management, which also includes the stimulation of blow-out formation. While Arens et al. (2010) demonstrated that coast line recession coincides with preservation of foredune volume (or even a local increase in volume), X-Beach modelling shows additional benefits of dynamic coastal management. Roelvink et al. (2009) and Pool (2010) suggest that the presence of low blowouts, while vulnerable to temporary flooding during storm surges, does not have a negative impact on safety in areas marked by the presence of a wide dune belt. A coastline with undulating foredunes is modelled to experience less severe dune scarping than a closed foredune in the form of a ‘sand dyke’ (Pool, 2009). A semi-open foredune is more effectively able to dissipate some of the destructive energy unleashed by storm waves and currents. Surge water can enter gaps and the energy contained in this water is distributed over a larger area. Landward of the frontal dunes, the water is absorbed quickly by the permeable subsoil, the associated energy is attenuated by dune vegetation, and the entrained sediment is deposited. A secondary dune row will prevent the storm-surge water from reaching vulnerable lowlands behind the dune belt.

The overall trends at Bergen aan Zee (steady seaward foredune migration) and Heemskerk (slow dune foot erosion), as observed by the Jarkus monitoring, are obscured by the impacts of major storm surges and by subsequent periods of beach and foredune recovery. A limitation in separating the erosive effects of storm surges from intervening recovery periods and from the long-term trend is the low (annual) temporal resolution of the Jarkus measurements. Pre- and post-surge measurements will include not only storm-surge effects, but also the effects of all other coastal processes that took place during the year between subsequent measurements, including entrapment of sand by dune grass planted at the dune foot. Earlier, Zhang et al. (2002) found a similar pattern as the ‘Heemskerk’ scenario of slow long-term erosion in their analysis of shoreline data from the U.S. East Coast. They noted that even following the most damaging storms, such as the Ash Wednesday Storm of 1962, beaches recover to positions matching their overall, century-scale trend. Zhang et al. (2002) concluded that barrier beaches would not experience long-term erosion, even when experiencing frequent major storms, if sediment supply were sufficient to keep up with the effects of relative sea-level rise. This conclusion is confirmed by our observations from Bergen aan Zee, which show pre-nourishment erosion up to 1990 but slow nourishment-related foredune progradation since then, interrupted but not reversed by brief erosive events.

An unwanted effect of the nourishments at Bergen aan Zee, and other places north of this town, concerns the introduction of lime-rich and coarser sands in a coast naturally dominated by finer-grained sands poor in $CaCO_3$. Stuijfzand et al. (2010) reported on geochemical and grain-size analyses of nourished sand at various places along the coast. In Bergen aan Zee, samples were taken just south of the town (about 1 km from the GPR profiles) in a transect from the high-water mark to about 400 m inland. They concluded that the nourished sand is not only coarser than the natural dune sand but also contains significantly less fines (<63 µm). Compared to the original dune sand, sediment with significantly higher concentrations of $CaCO_3$ and elements P, S, As, Co and Ni has been introduced on the beach. The nourished sand has been transported up to 300 m inland, lowering organic-matter content. The implications of these nourishment-related changes are addressed in ecological studies (KLZ-ecology programme/OBN programme).

Finally, the effects of the nourishments have practical consequences at Bergen aan Zee. The seaward shift of the dune foot (30-50 m since 1990) is currently becoming a problem for the semi-permanent beach restaurants. These restaurants are placed on long wooden poles driven into the beach sand and, consequently, are fixed in position. In spring, the poles have to be dug out to allow operation of the restaurants in the summer season. Removing part of the accreted foredune leads to higher costs for restaurant owners.

# 6 Conclusions

In revealing the internal architecture of foredunes, GPR helps to establish the origin and preservation of stacked sedimentary units that make up the foredunes. Thus, GPR profiles are instrumental in explaining Jarkus profiling data in terms of responsible coastal processes. This combination of techniques can be used to optimise coastal-management policies.

At the Heemskerk aan Zee site, sand nourishment has never been implemented. During the period 1965-2008, the foredune foot migrated landward at an average rate of 1.0 m/yr. Arens et al. (2010) demonstrated that the total volume of the foredune has been more or less stable since 1997; the loss on the seaward side has been compensated mostly by accretion at the landward side of the frontal dune. The precise geometry of this accreted volume can clearly be imaged by GPR.
Pool (2009) showed that the mode of dynamic preservation applied at Heemskerk, allowing limited erosion and blow-out development, does not lead to enhanced safety risks. The large blow-outs carved in the foredune can evolve into temporary breaches during extreme storm surges. Surge water entering such gaps experiences rapid dissipation of the associated wave energy, and a non-uniform foredune configuration reduces overall dune-foot erosion.

At Bergen aan Zee, Jarkus and GPR data show a distinct, nourishment-related net growth of the foredune volume over the years, with high year-to-year variability. The dune foot has migrated 30-50 m in a seaward direction over the period 1990-2008.
The integration of Jarkus and GPR data makes it possible to establish the year of origin of sand volumes, and to attribute textural and compositional properties to these volumes. The data show that 21 % of the accreted volume originates from water-lain embankments constructed in 1990/91, 11 % from 1993 beach sands, 36 % from year-2000 nourishments (partly water-lain and therefore in situ, mostly redistributed by wind) and the remaining 32 % from the period 2001-2008 (entirely wind-redistributed nourishment sand). The net volume of accumulation ranges between 180 and 233 m3/m over a shore-parallel distance of 530 m.
Almost all sand of the nourishments applied prior to 2000 has been washed away. Analysis of meteorological and marine data suggests that the 1999 storm surges are most likely responsible for erosion of all post-1990 nourished material still present on beach and foredune at that time. After 2000, structural accumulation has taken place in the form of wind-blown nourishment sand, not only in the nourishments years 2000 and 2005. This accumulation can be attributed to extended sediment supply from shoreface nourishments and to favourable meteorological conditions.

Field observations during a significant storm surge in 2007 suggest that wind-blown nourishment sands are more prone to wave erosion than water-lain nourishment sands. Type and composition of the sand are very important, and may be used not only to predict the longevity of nourished sediment volumes, but also to assess ecological effects in the frontal dunes.

It is recommended to combine a diversity of techniques and approaches, including GIS based studies, Jarkus measurements, GPR and meteorological reconstructions in beach-nourishment evaluations. Following this approach, morphological and ecological effects of nourishment programmes will become clearer, allowing fine-tuning of nourishment strategy.

# 7 Vocabulary

| | |
|---|---|
| Diffraction | Disturbance in GPR profiles caused by point objects or objects/structures of limited spatial extent (eg. debris or roots). The shape can be used to determine the velocity of the radar signal in the subsurface |
| Embankment | Erosion buffer placed on the higher parts of the beach against the foredune. Also referred to as shoulder or sand banquet (Hillen & Roelse, 1995). In Dutch named *banket* |
| Listric | A curved, spoon-shaped form, with dip decreasing with depth |
| Radar facies | Subunits in ground-penetrating radar profiles that are defined as units of particular reflection properties |

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